

Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

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Agenda

Summary Overview

Requirements Derivation

WBS Task Details

Objective

Define and initiate a long-term program to mature six inter-linked critical technologies for future UVOIR space telescope mirrors to TRL6 by 2018 so that a viable flight mission can be proposed to the 2020 Decadal Review.

- *Large-Aperture, Low Areal Density, High Stiffness Mirrors:* 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.
- *Support System:* Large-aperture mirrors require large support systems to ensure that they survive launch and deploy on orbit in a stress-free and undistorted shape.
- *Mid/High Spatial Frequency Figure Error:* A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.
- *Segment Edges:* Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.
- *Segment-to-Segment Gap Phasing:* Segment phasing is critical for producing a high-quality temporally stable PSF.
- *Integrated Model Validation:* On-orbit performance is determined by mechanical and thermal stability. Future systems require validated performance models.

We are pursuing multiple design paths give the science community the option to enable either a future monolithic or segmented space telescope.

Approach

Technology must enable mission capable of doing both general astrophysics and ultra-high contrast observations of exoplanets.

Outstanding team of academic, industry & government with expertise:

- UVOIR astrophysics and exoplanet characterization,
- monolithic and segmented space telescopes, and
- optical manufacturing and testing.

Integrate science & systems engineering to:

- derive engineering specifications from science measurement needs and implementation constraints;
- identify technical challenges in meeting these specifications;
- iterate between science and systems engineering to mitigate challenges; and
- prioritize the challenges.

Systematically mature TRL of prioritized challenges using

- design tools to construct analytical models and
- prototypes/test beds to validate models in relevant environments.

Goals

Defined quantifiable goals for each of the six key technologies:

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:

- make 2 200-mm subscale mirrors via a process traceable to 500 mm deep mirrors

Support System:

- produce pre-Phase-A point designs for candidate primary mirror architectures; and
- demonstrate specific actuation and vibration isolation mechanisms

Mid/High Spatial Frequency Figure Error:

- ‘null’ polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2 C operational temperature.

Segment Edges:

- derive edge specifications traceable to science requirements; and
- demonstrate an achromatic edge apodization mask.

Segment to Segment Gap Phasing:

- develop models for segmented primary mirror performance; and
- test prototype passive and active mechanisms to control unconstrained, damped and constrained gaps to ~ 1 nm rms.

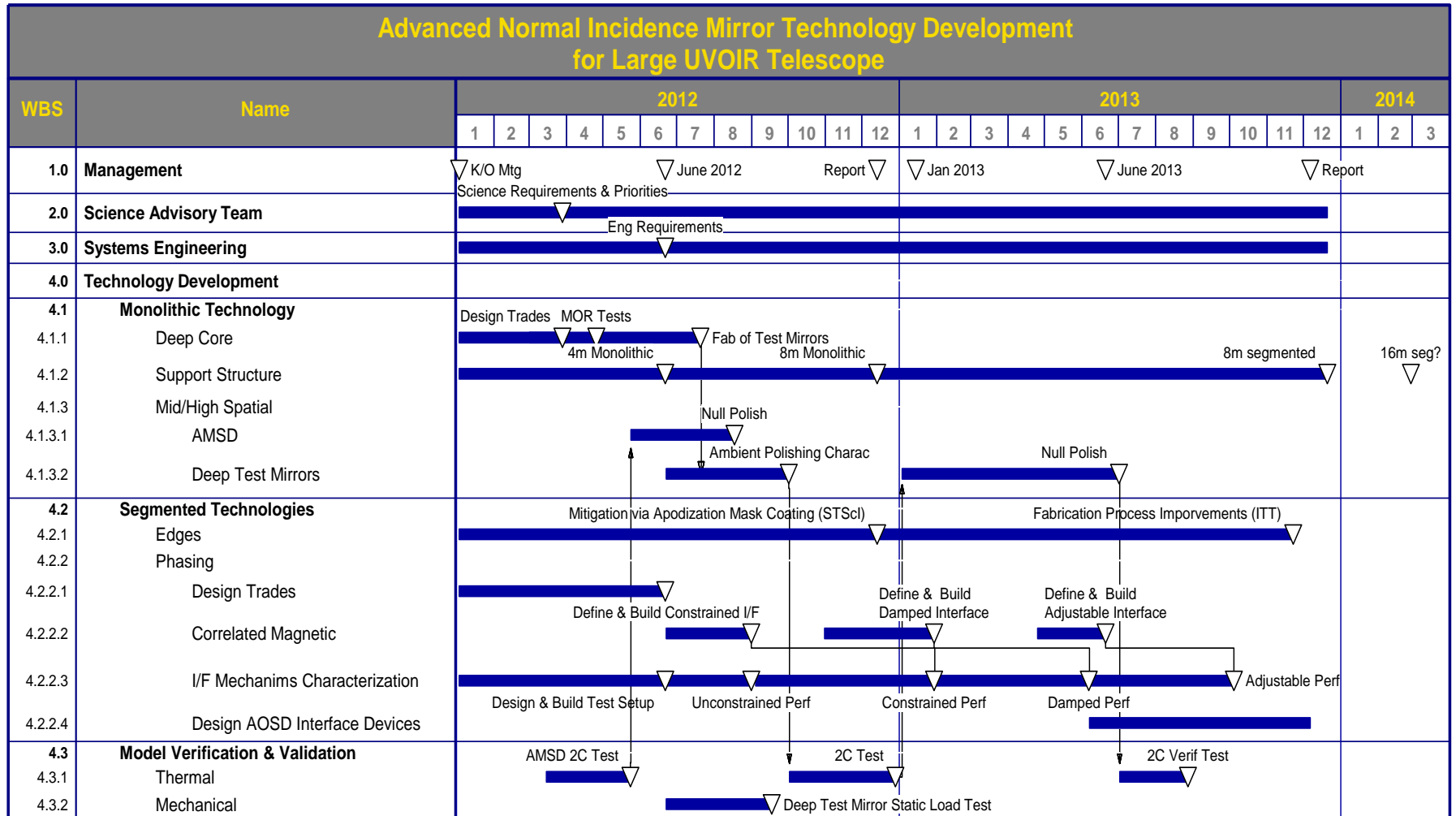
Integrated Model Validation:

- validate thermal model by testing the AMSD and deep core mirrors at 2 C; and
- validate mechanical models by static load test.

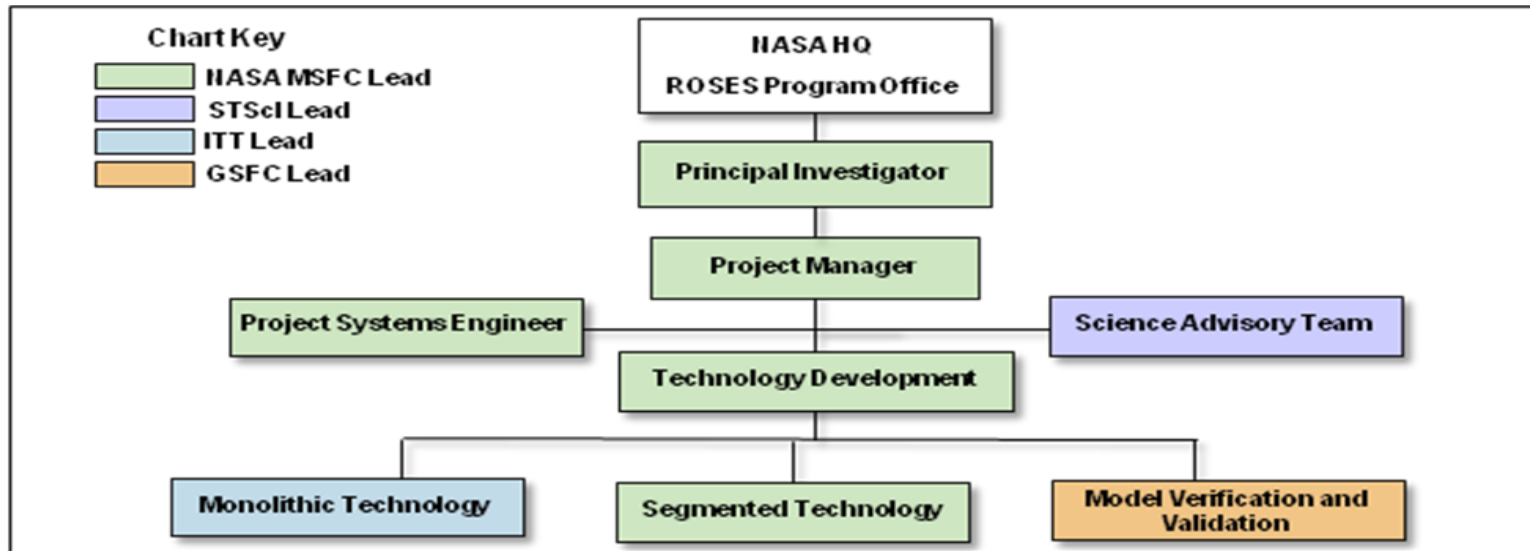
Work Breakdown Structure

Project is managed according to WBS.

Each quantitative Milestone is scheduled.



Project Organization



Principle Investigator		Systems Engineering		
Dr. H. Philip Stahl	MSFC	SE Lead	Dr. W. Scott Smith	MSFC
		Integrated Modeling	Gary Mosier	GSFC
Science Advisory		Engineering		
Dr. Marc Postman	STScI	ITT Project Manager	Calvin Abplanalp	ITT
Dr. Remi Soummer	STScI	Systems Engineer/Sys. Lead	Keith Havey	ITT
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		Structure Mechanical	William Arnold	Jacobs
		Institutional Co-I	Larry Fullerton	CMR

Requirement Derivation:

From Science Needs to Technical Challenges

Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions

Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope

Science Question	Science Requirements	Measurements Needed	Requirements
Is there life elsewhere in Galaxy?	Detect at least 10 Earth-like Planets in HZ with 95% confidence.	High contrast ($\Delta\text{Mag} > 25$ mag) SNR=10 broadband ($R = 5$) imaging with IWA ~ 40 mas for ~ 100 stars out to ~ 20 parsecs.	≥ 8 meter aperture Stable 10^{-10} starlight suppression
	Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets	High contrast ($\Delta\text{Mag} > 25$ mag) SNR=10 low-resolution ($R=70$ -100) spectroscopy with an IWA ~ 40 mas; spectral range 0.3 – 2.5 microns; Exposure times < 500 ksec	~ 0.1 nm stable WFE per 2 hr ~ 1.3 to 1.6 mas pointing stability
What are star formation histories of galaxies?	Determine ages (~ 1 Gyr) and metallicities (~ 0.2 dex) of stellar populations over a broad range of galactic environments.	Color-magnitude diagrams of solar analog stars ($V_{\text{mag}} \sim 35$ at 10 Mpc) in spiral, lenticular & elliptical galaxies using broadband imaging	≥ 8 meter aperture Symmetric PSF
What are kinematic properties of Dark Matter	Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies	0.1 mas resolution for proper motion of ~ 200 stars per galaxy accurate to ~ 20 $\mu\text{as/yr}$ at 50 kpc	500 nm diffraction limit 1.3 to 1.6 mas pointing stability
How do galaxies & IGM interact and affect galaxy evolution?	Map properties & kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to ~ 10 Mpc.	SNR = 20 high resolution UV spectroscopy ($R = 20,000$) of quasars down to FUV mag = 24, survey wide areas in < 2 weeks	≥ 4 meter aperture
How do stars & planets interact with interstellar medium?	Measure UV Ly-alpha absorption due to Hydrogen “walls” from our heliosphere and astrospheres of nearby stars	High dynamic range, very high spectral resolution ($R = 100,000$) UV spectroscopy with SNR = 100 for $V = 14$ mag stars	500 nm diffraction limit Sensitivity down to 100 nm wavelength.
How did outer solar system planets form & evolve?	UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth	SNR = 20 - 50 at spectral resolution of $R \sim 10,000$ in FUV for 20 AB mag	

Representative Missions

Four ‘representative’ mission architectures achieve Science:

- 4-m monolith launched on an EELV,
- 8-m monolith on a HLLV,
- 8-m segmented on an EELV, or
- 16-m segmented on a HLLV.

Should also look at 8-m segmented on HLLV.

Mass

Mass is the most important factor in the ability of a mirror to survive launch and meet its required on-orbit performance.

More massive mirrors are
stiffer and thus easier and less expensive to fabricate;
more mechanically and thermally stable.

Technology Challenges are derived directly from Science Requirements to Mission Requirements taking into account Launch Vehicle Constraints

Table 3.1: Science Requirement to Technology Need Flow Down

Science	Mission	Constraint	Capability	Technology Challenge
Sensitivity	Aperture	EELV 5 m Fairing, 6.5 mt to SEL2	4 m Monolith	4 m, 200 Hz, 60 kg/m ²
				4 m support system
		8 m Segmented		2 m, 200 Hz, 15 kg/m ²
				8 m deployed support
		HLLV-Medium 10 m Fairing, 40 mt to SEL2	8 m Monolith	8 m, <100Hz, 200kg/m ²
				8 m, 10 mt support
		16 m Segmented		2-4m, 200Hz, 50kg/m ²
				16 m deployed support
		HLLV-Heavy 10 m Fairing, 60 mt to SEL2	8 m Monolith	8m, <100Hz, 480kg/m ²
				8 m, 20 mt support
	2 hr Exposure	Thermal 280K \pm 0.5K 0.1K per 10min	< 5 nm rms per K	low CTE material
			> 20 hr thermal time constant	thermal mass
		Dynamics TBD micro-g	< 5 nm rms figure	passive isolation
				active isolation
	Reflectance	Substrate Size	> 98% 100-2500 nm	Beyond Scope
High Contrast	Diffraction Limit	Monolithic	< 10 nm rms figure	mid/high spatial error
		Segmented	< 5 nm rms figure	fabrication & test
			< 2 mm edges	edge fabrication & test
			< 1 nm rms phasing	passive edge constraint
				active align & control

Space Launch System (SLS)

Space Launch System (SLS) Cargo Launch Vehicle specifications

Preliminary Design Concept

8.3 m dia x 18 m tall fairing

70 to 100 mt to LEO

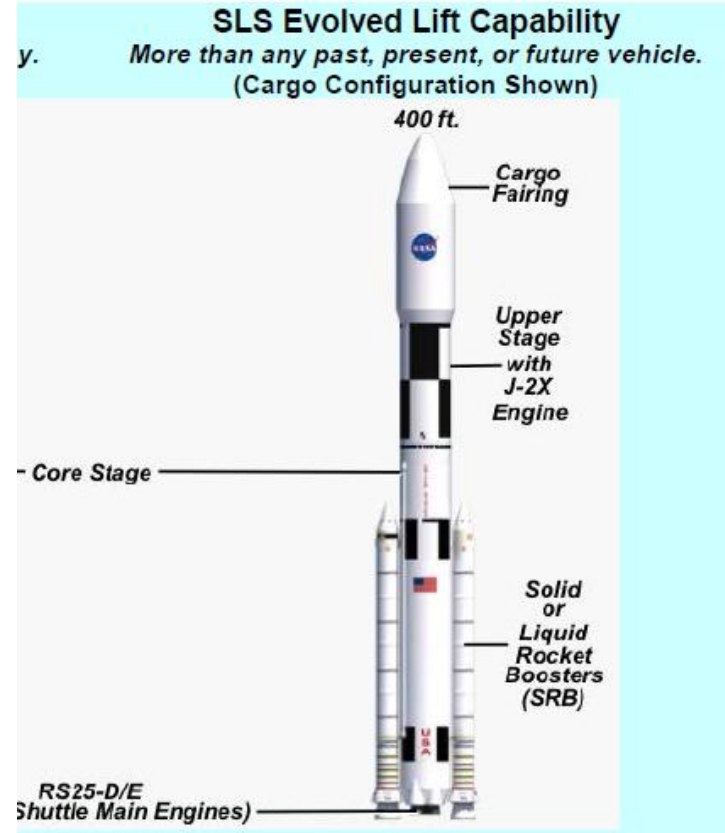
consistent with HLLV Medium

Enhanced Design Concept

10.0 m dia x 30 m tall fairing

130 mt to LEO

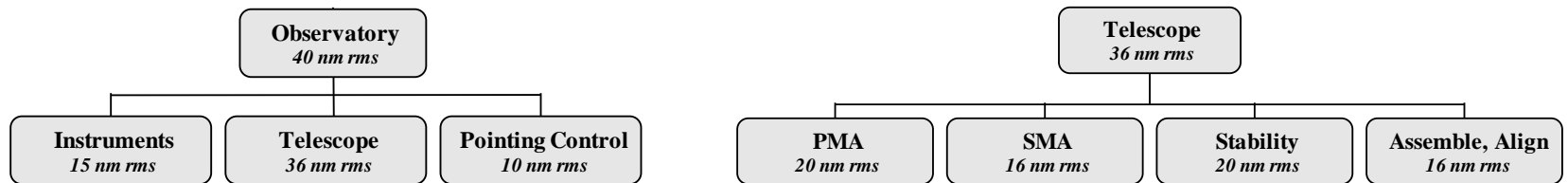
consistent with HLLV Heavy



HLLV Medium could launch an 8-m segmented telescope whose mirror segments have an areal density of 60 kg/m².

Primary Mirror Total Surface Figure Requirement

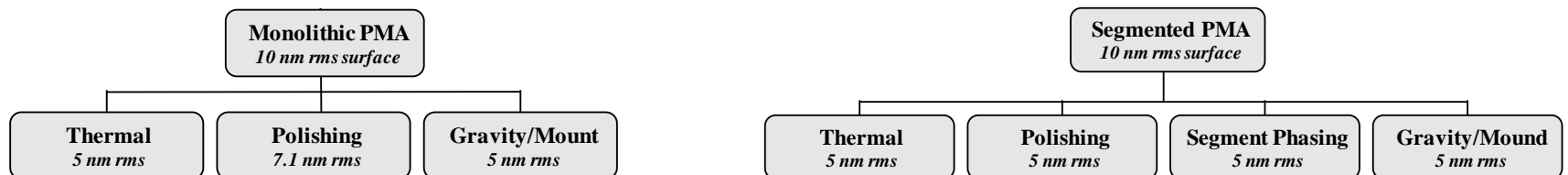
Primary Mirror requirements are derived from 500 nm diffraction limited and PSF stability requirements.



Key technical requirements are:

- 10 nm rms wavefront Pointing Stability
- 20 nm rms wavefront Thermal & Mechanical Stability
- 20 nm rms wavefront primary mirror

Regardless whether monolithic or phased, PM must have a 10 nm rms surface. Segmenting increases complexity and redistributes the error allocations.



WBS Task Discussion

WBS 2.0 Science Advisory Team

Science team works with Engineering to:

- derive (and/or confirm) engineering specifications for advanced normal incidence mirrors which flow down from the astrophysical measurement needs and flow up from implementation constraints;
- collaborate with systems engineering to mitigate these challenges via architectural implementation trades; and
- prioritize which challenges should be solved first.

Science meets 2X per year with Engineering to review progress, assess priorities, and plan future efforts

WBS 2.0 Science Advisory Team

Key Questions for the Science Team:

- 1) Based on current science needs, do you recommend any changes or additions to 6 critical technologies or their goals?
- 2) Based on current science needs, do you recommend any changes or additions to requirement measurement capabilities, technical requirements, candidate mission architectures or key technical challenges?
- 3) Do you agree with the milestone prioritization?
- 4) What are specifications for a segmented PM?
 - segment edge quality,
 - segment-to-segment gap control, and
 - phasing stability.

WBS 3.0 Systems Engineering

Systems Engineering working with Science:

- derives engineering mirror specifications to achieve on-orbit performance requirements;
- identifies technical challenges in meeting these specifications;
- prioritize technology development using a systems perspective to determine which technologies will yield the greatest on-orbit performance improvement; and
- define metrics, evaluate their TRL, and assess their advance.

Engineering meets 2X per year with Science to review progress, assess priorities, and plan future efforts

WBS 3.0 Systems Engineering

Systems Engineering will

- develop thermal & mechanical models of candidate mirror systems including substrates, structures, and mechanisms;
- validate models by test of full- and subscale components in relevant thermo-vacuum environments.

Specific analyses include:

- maximum mirror substrate size, first fundamental mode frequency (i.e., stiffness) and mass required to fabricate without quilting, survive launch, achieve stable pointing and maximum thermal time constant;
- segment edge dimensions and roll; and
- segment-to-segment gap dimensions, phasing and stability.

WBS 4.0 Technology Development

WBS 4.0 develops technology

- 4.1 Monolithic Mirror Technology
- 4.2 Segmented Mirror Technology
- 4.3 Model Verification and Validation

Enables our 4 baseline options:

- 4-m monolithic mirror launched by an EELV;
- 8-m monolithic mirror launched by a HLLV;
- 8-m segmented mirror launched by an EELV; and
- 16-m segmented mirror launched by a HLLV.

Same technology can also enable 8-m on HLLV.

WBS 4.1 Monolithic Technologies

Monolithic mirror technology is required to manufacture, test, launch, and operate a 4 or 8-m monolithic mirror also 2-m class mirror segments.

WBS 4.1 matures the 3 key monolithic mirror challenges:

- 4.1.1 Deep Core Mirror Substrate
- 4.1.2 Mirror Support Structure
- 4.1.3 Mid/High Spatial Frequency Surface Errors

WBS 4.2 Segmented Technologies

Segmented mirror technology is required to assemble, align, phase, and operate a segmented mirror as an integrated unit to UVOIR tolerances.

WBS 4.2 matures the 2 key segmented mirror challenges:

- 4.2.1 Edge Control
- 4.2.2 Gap Phasing Control

WBS 4.3 Model Verification & Validation

Models are required to predict on-orbit performance for pointing stability, jitter, and thermal-elastic stability, as well as vibro-acoustics and launch loads. Performance data is required to verify and validate models.

WBS 4.3 matures the 2 key modeling challenges:

- 4.3.1 Thermal Model Verification
- 4.3.2 Mechanical Model Verification

WBS 4.1.1 Deep Core Substrate

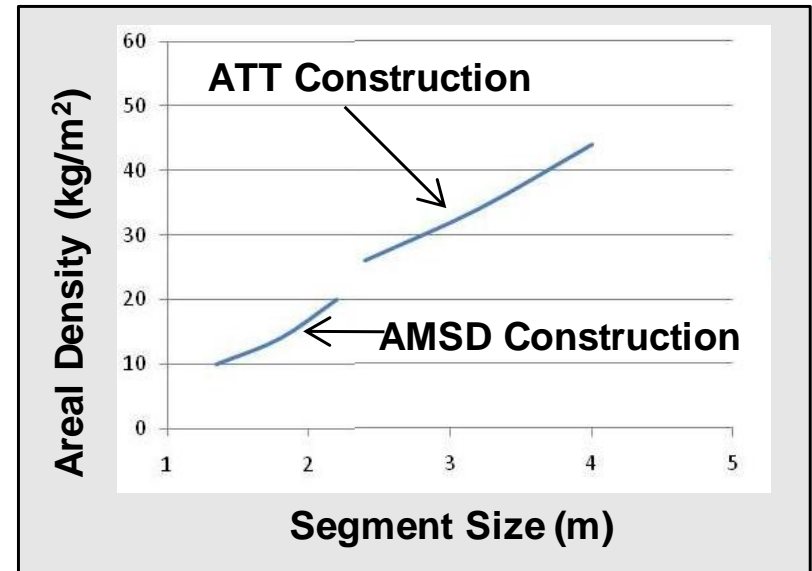
Need: 500 mm thick mirror substrate.

4 m PM requires substrate with areal density of $<60 \text{ kg/m}^2$ & $\sim 200 \text{ Hz}$ first mode. Analysis indicates this can be achieved with a 500 mm thick mirror. For 8-m, this is an upper thickness limit.

SOA: 300 mm deep substrates

Starting: TRL3/4

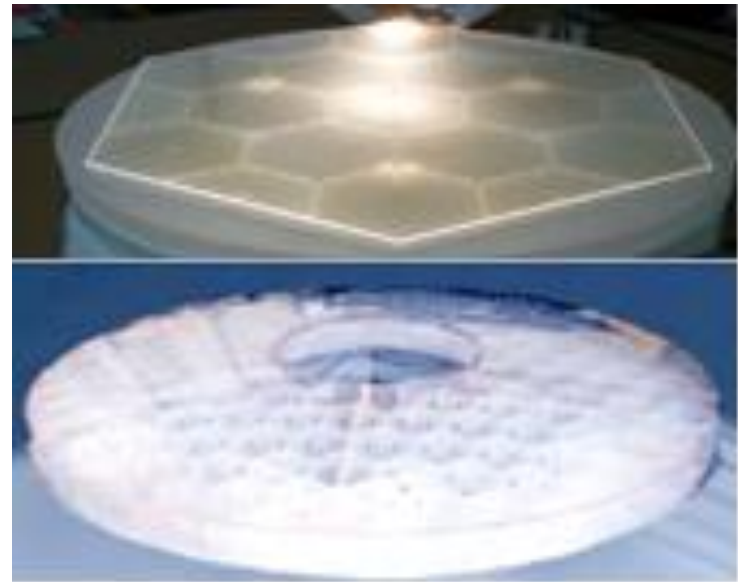
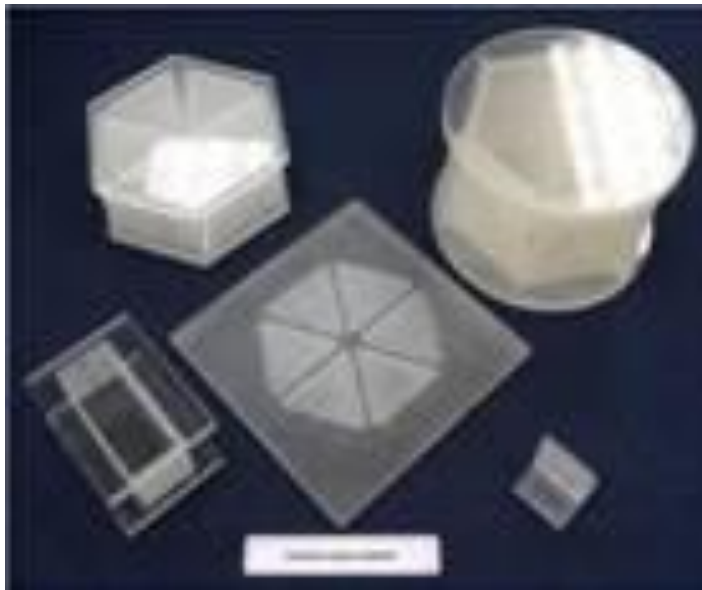
2.4 m is TRL9 (HST), Kepler is 1.4m – both are sub-scale.



WBS 4.1.1 Deep Core Substrate

Milestone: demonstrate innovative process to make glass cores with required areal density that can be scaled to 500 mm deep.

Approach: manufacture two 200 mm deep subscale substrates from separate 100 mm thick cores with different facesheet designs (plano/plano AMSD-style & pocket milled ATT-style).



WBS 4.1.2 Support Structure

Need: System to support mirror during launch and deploy it into an on-orbit strain free state; maintain operational wavefront and pointing stability.

SOA: Kepler 1.4 m support system

Starting: TRL3/4

Kepler support system is TRL9, but it is sub-scale.

Milestone: Pre-Phase-A point designs for potential 4-m and 8-m monolithic primary mirrors and an 8-m segmented mirror.

Approach:

Design structure based on substrate designs, launch vehicle constraints and performance requirements.

Design, build & demonstrate a two-stage active strut/actuator.

WBS 4.1.3 Mid/High Spatial Frequency

Need: < 10 nm rms surface mirror at 2C

SOA:

AMSD at < 10 nm rms and ATT at < 20 nm rms at 20C

Hubble, 7.8 nm rms at 20C

4m & 8m ground telescope mirrors at ~ 10 nm rms at 20C

Starting: TRL4 for 1.5 m; TRL 3 for 4 m or larger.

AMSD, ATT & HST are sub-scale & not at operational temperature.

Ground 4m & 8m mirrors are full size, but not flight areal density.

Milestone: polish traceable substrates to UVOIR tolerances at their anticipated operating temperature of 2 C.

Approach:

Create mechanical and thermal models

Test AMSD mirror at 2C and cryo-null polish via traceable process

Demonstrate on 4.1.1 sub-scale mirrors process (traceable to 2m, 4m or 8m mirrors) to polish without introducing quilting

WBS 4.2.1 Edge Control

Need: TBD by Science and Systems Engineering

SOA: Keck is 2 mm (but substrates are 400 Hz); JWST is close to 5 mm; AMSD was 10 mm; QED & Zeeko SBIRs did 2 mm

Starting: TRL3 to 6 depending on Requirement

Milestone:

- Define Requirement

- Demonstrate apodization concept via a test article.

Approach:

- Write an amplitude apodization mask on the edge of a mirror and test its impact on edge diffraction.

WBS 4.2.2 Gap Phase Control

Need: < 5 nm rms segment to segment stability

SOA: JWST, passive, 20 nm 50 Hz rocking mode; Keck, active, < 20 nm rms 50 Hz; ITT AOSD, active, < 10 nm rms 30 Hz; LAMP, active, classified in Vacuum.

Starting: TRL3/4

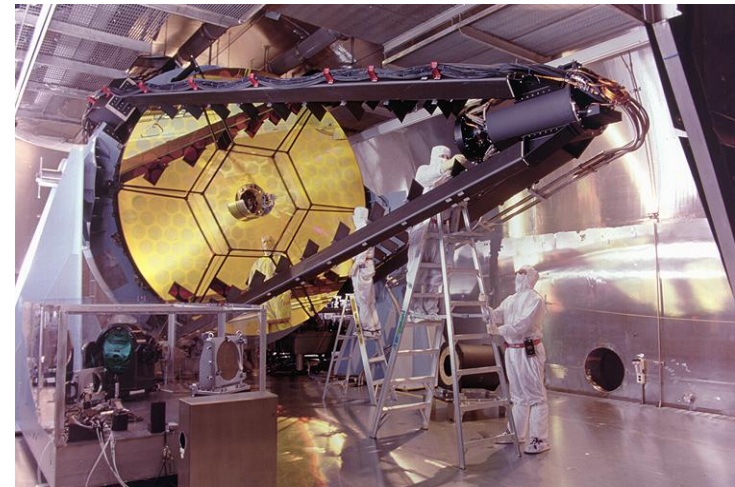
UVOIR Requirement not achieved.

Milestone:

Demonstrate Active Strut (WBS 4.1.2)

Quantify utility of Correlated Magnetic Interfaces

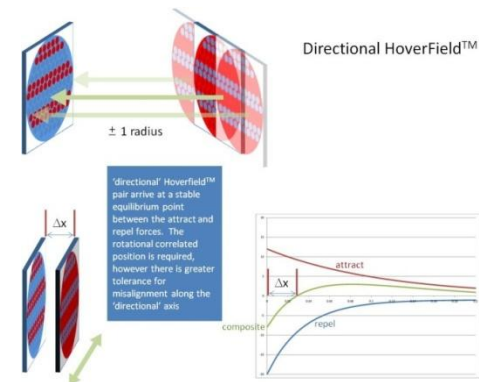
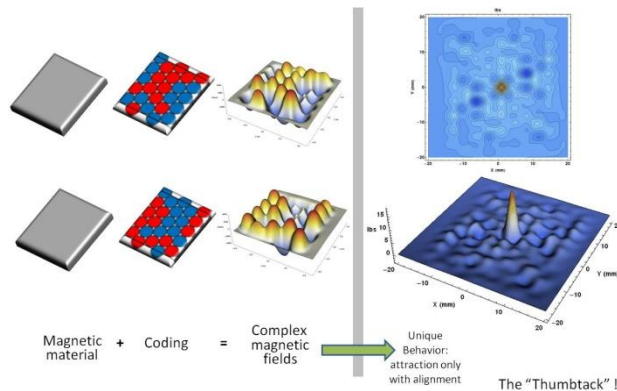
Approach: design, build and test dynamic dampening devices on sub-scale test-bed and on ITT AOSD test-bed.



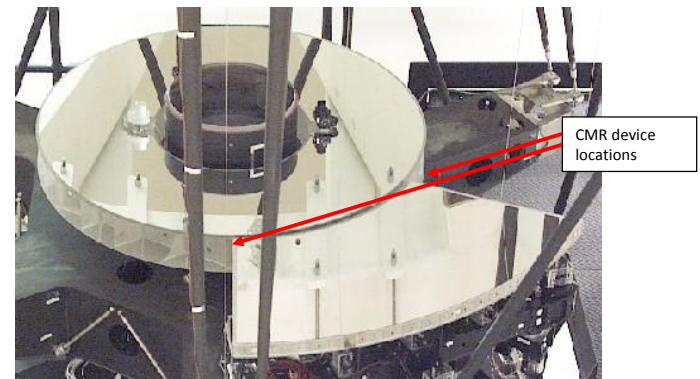
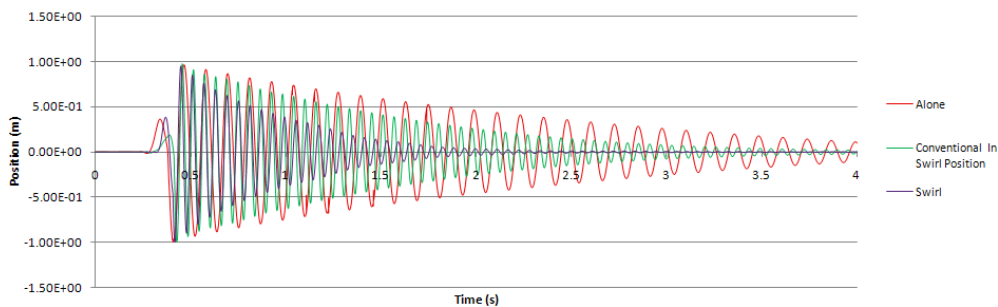
Correlated Magnetic (CM) Interface

CMs are useful for vibration isolation & motion constraint.

CM can be designed to constrain interface to a single symmetry point; rotate about a symmetry point; or move linearly in one direction but not the orthogonal direction – similar to a mechanical flexure.



Swirl Comparison



WBS 4.3 Integrated Modeling

Need: Predict on-orbit performance

SOA:

JWST (AMSD, Flight PMSAs, BSTA 4% match);

Air Force Structural Vibration Modeling and Verification (SVMV)

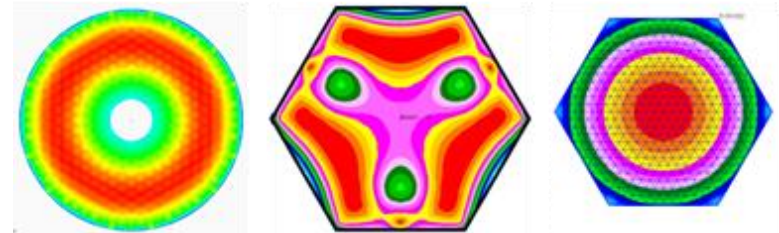
Starting: TRL4/5

UVOIR Requirement not achieved.

Milestone:

Validate Thermal Model

Validate Mechanical Model



Approach:

Thermal model predicts AMSD figure sensitivity of 5 nm rms/K.

Prediction will be validated at the MSFC XRCF. Additionally, thermal figure stability will be quantified.

Mechanical model will be validated via static load test.